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AIRCRAFT ENCOUNTERS WITH MOUNTAIN WAVE-INDUCED CLEAR AIR TURBULENCE: HINDCASTS AND OPERATIONAL FORECASTS USING AN IMPROVED GLOBAL MODEL

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1. INTRODUCTION

Mountain waves are important dynamical processes that require global modeling and forecasting. Variable distributions of mountain wave-induced drag and diffusion modify both the fine-scale and synoptic-scale circulations of the atmosphere. Global numerical weather prediction (NWP) models cannot resolve mountain waves and so must parameterize mountain wave effects globally to improve both their climatologies and forecast skill (Palmer et al. 1986; Zhou et al. 1996). Breaking mountain waves can also generate severe clear-air turbulence, thereby endangering aviation (Lilly 1978; Ralph et al. 1997).

Mountain waves are particularly important in the stratosphere and mesosphere. Breaking waves drive global circulation patterns at these heights (Norton and Thuburn 1999), while the perturbations dominate the mesoscale stratospheric dynamics around undular terrain (Eckermann and Preusse 1999; Whiteway 1999), triggering stratosphere-troposphere exchange [Lamarque et al., 1996] and formation of ozone-destroying polar stratospheric clouds [Carslaw et al., 1999]. Thus, global models of their effects are needed not just within the troposphere, but up to mesospheric heights of ~100 km.

This work focuses on one such model, known as the Mountain Wave Forecast Model (MWFM), which we have developed and extended recently. We focus here on some recent applications of the model in forecasting mountain wave-induced turbulence for aviation. More details on the model can be found on the web at http://uap-www.nrl.navy.mil/dynamics/html/mwfm.html.

2. BASIC MODEL (MWFM V1.0)

The model was initially developed by Bacmeister (1993), who outlines the way it calculates global distributions of mountain waves forced by flow over dominant features in the Earth's topography. The code was inexpensive enough computationally to provide global output up to mesospheric altitudes. The key simplification was to decompose the Earth's topography into a list of quasi-two dimensional ridge features, since many major mountain ranges approximate this general form (e.g., the Andes, the Shenandoahs). Each ridge element is represented by a box, or "ridgelet," of a given height, width and horizontal orientation. These parameters determine the amplitude and wavelengths of any mountain wave forced by flow across it. A two-dimensional hydrostatic gravity wave model was used to propagate the wave away from the parent ridge through upper-level wind and temperature profiles. A saturation model was used to calculate regions of wave breaking and mean-flow drag.

The model's ability to run quickly and to calculate zones of wave breaking in arbitrary atmospheres prompted further development, then tests as to whether it could forecast mountain wave-induced turbulence in the stratosphere (Bacmeister et al. 1994). It had been known that severe turbulence encounters by high-altitude stratospheric aircraft often seemed correlate with mountain waves (Lilly and Lester 1974; Ehernberger 1987). Model hindcasts were compared with documented turbulence encounters by NASA's ER-2 research aircraft, and revealed encouraging agreement (Bacmeister et al. 1994). Given the structural vulnerability of the ER-2 to severe turbulence and its regular intercepts of mountain waves during research missions (Bacmeister et al. 1990; Eckermann et al. 2000), the model has been used regularly in NASA missions with the ER-2 since ~1994. This operational version of the model has come to be known as The Mountain Wave Forecast Model (MWFM V1.0).

3. IMPROVED MODEL (MWFM V2.0)

For MWFM to run in a rapid operational global forecasting mode at stratospheric altitudes, a number of simplifying approximations were necessary, some of which were listed in section 4 of Bacmeister et al. (1994). Advances in computing capabilities, together

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with an expanding range of potential forecasting applications, have led us to explore and implement new algorithms that describe mountain wave dynamics more accurately. Our major advance has been to generalize the model, from forecasting only hydrostatic plane mountain waves above two-dimensional ridges, to generally nonhydrostatic mountain wave patterns radiated from three-dimensional topography that can penetrate large distances downstream.

Our approach involves numerical ray-tracing. Previous work has shown that three-dimensional "ship wave" cloud patterns produced by flow over circular three-dimensional mountain can be understood to first order using gravity wave ray-tracing equations (Gjevik and Marthinsen 1978; Smith 1980). However, synthesis of full three-dimensional wave patterns, which requires accurate calculations of wave amplitudes along each ray, has proved difficult.

Recently, Shutts (1998) made progress by comparing analytical and numerical simulations of three-dimensional mountain waves in a turning wind profile with simpler ray-based calculations. He showed that propagational spreading of wave patterns into progressively larger horizontal areas had a large influence on the evolution of wave amplitude with height. We have developed a general ray-based solution method for waves radiated from isolated three-dimensional sources (Broutman et al. 2000), which accurately reproduces the results of the specific problem addressed by Shutts (1998). In particular, it demonstrates that ray solutions of the trajectory, refraction and wave action conservation equations can yield fast accurate forecasts of nonplanar mountain wave fields radiated from three-dimensional orography. A full three-dimensional nonhydrostatic ray-tracing algorithm with a one-dimensional (vertical) wave action solution with wave breaking criteria (e.g. Marks and Eckermann 1995) has been built into the MWFM 2.0 code. Further refinements and extensions are being tested.

4. STRATOSPHERIC FORECASTING DURING SOLVE

NASA's SAGE III Ozone Loss and Validation Experiment (SOLVE) was a stratospheric airborne research campaign based in Kiruna, Sweden last winter. It utilized the ER-2 during the second and third deployments (January-March, 2000). The area of flight operations included significant orography: e.g., the Norwegian Mountains, northern Urals, Novaya Zemlya, Spitzbergen and Iceland. When combined with the remote hostile Arctic environment, the polar night, and negotiating Russian airspace, zones of severe mountain wave-induced turbulence were a priority forecast parameter for ER-2 flight planning during the campaign.

In pre-mission planning, we used MWFM 1.0 to investigate the statistics of mountain wave-induced turbulence at ER-2 cruise altitudes in and around Kiruna airport during previous winters. Figure 1 shows monthly mean wave-induced turbulence at 50-70 hPa (typical ER-2 cruise levels) for January-February of 1996-98.

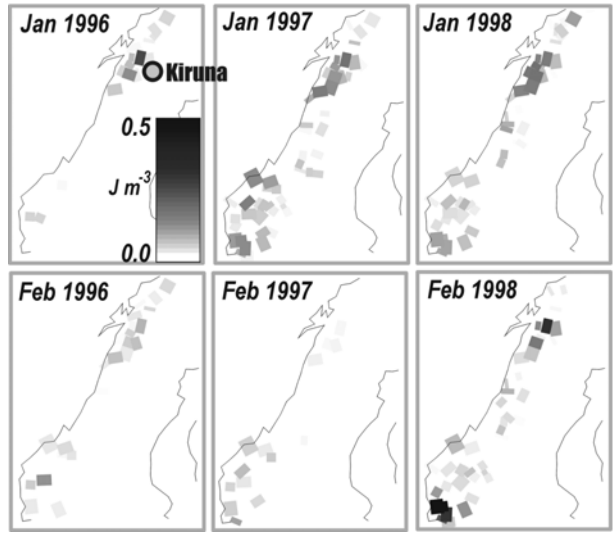

FIG. 1. Average mountain wave-induced turbulence at 50-70 hPa (~18-21 km) over Scandinavia for January and February of 1996-98, from MWFM 1.0 hindcasts, based on daily 2.5°x2° STRATF assimilations at 12Z from NASA's Data Assimilation Office.

Several features are worth noting. First, mean values rarely exceed 0.5 J m^{-3} anywhere along the Norwegian coast. Previous experience has suggested that values ≥1 J m^{-3} represent a potentially hazardous flying environment for the ER-2. Thus, the results suggest that, despite the large mountains and frequently intense stratospheric mountain waves, mean wave-induced turbulence levels are not huge, and thus ER-2 flights to/from Kiruna do not pose a recurrent safety hazard. Second, the results reveal considerable day-to-day and interannual variability. For instance, February 1998 shows some of the largest mean turbulence values near Kiruna, whereas February 1997 shows almost no turbulence at all. The conclusion is that there are no reliable climatological features here to guide flight planning, and thus daily turbulence forecasts are essential.

Pre-SOLVE forecasting work with MWFM 1.0 also revealed that mountain wave-induced temperature perturbations often drop stratospheric temperature sufficiently low to form polar stratospheric clouds (PSCs) in and around Kiruna (Carslaw et al. 1999). Given their pivotal role in ozone loss, locating and sampling PSCs with the ER-2 during SOLVE was a major mission priority. So, while it was imperative that the ER-2 avoided mountain wave-induced turbulence, ER-2 flights through nonturbulent PSC-producing mountain waves were considered highly desirable scientifically.

Thus, SOLVE presented particular forecasting challenges for the MWFM, and so we undertook our most complete operational forecasting effort to date. Forecasts of turbulence and PSC formation potential from both the MWFM 1.0 and 2.0 were run automatically each day at the Naval Research Laboratory, once global forecast products came online. Tailored simulations were also conducted in the field in Kiruna, in response to requests from flight planners and science teams. To

provide reliability checks, we issued MWFM forecasts based on outputs of three global forecast models: the National Center for Environmental Prediction (NCEP), NASA's Data Assimilation Office (DAO) GEOS-DAS forecasting model, and the Navy Operational Global Atmospheric Prediction System (NOGAPS). Furthermore, we compared our wave amplitude predictions with parallel mesoscale model forecasts.

The resulting forecasting effort was very successful. ER-2 flights were often modified to avoid potentially turbulent air. The ER-2 conducted 16 long-duration flights (up to 8 hours) during the mission (including ferry flights), often through regions where MWFM forecast large mountain waves but little if any turbulence. The ER-2 intercepted no severe clear air turbulence at any time during the mission, despite encountering and measuring some large mountain waves over Kiruna, the northern Urals and Spitzbergen. Full analysis and results will be presented elsewhere. All mesoscale forecasts during the mission are archived at http://grytviken.leeds.ac.uk/~mesoscale/.

5. TROPOSPHERIC TURBULENCE FORECASTS

During SOLVE, NASA's DC-8 also flew a large number of long duration science missions. Though much less critical for DC-8 safety, MWFM turbulence forecasts were also requested and provided at DC-8 cruise altitudes (~250-200 hPa) and were used in flight planning. Furthermore, we have had continual interest from the gliding community in providing daily forecasts of mountain wave-induced "lift" in the lower and middle troposphere. We started providing these forecasts in 1998, and have had quite positive feedback about them from glider pilots.

While clear-air turbulence alerts and forecasting algorithms are provided by many agencies for aviation, these indices either do not include the effects of mountain waves or else use very simple formulae to predict potential effects. Given our perceived success in forecasting mountain wave-induced stratospheric turbulence and tropospheric mountain wave lift for the gliding community, MWFM forecasts of mountain wave-induced turbulence might be useful for conventional tropospheric aviation.

If the forecasts were to be valid anywhere in the troposphere, we believe that they are most likely to hold in the middle and upper troposphere, away from possible nonlinear effects close to orography that MWFM does not currently model. To test this, we worked through records of turbulence incidents from the National Transportation Safety Board (NTSB), searching for unexplained encounters at cruise altitudes that might have been caused by mountain waves. We consider two such cases here, which indicate that MWFM forecasts of tropospheric turbulence may hold some promise.

a. Alaska Airlines Flight 67: December 22, 1996

This Alaska Airlines Boeing 737 flight took off from Juneau, Alaska at ~6:10 p.m. on 22 December, 1996, and headed for Anchorage at a cruise altitude of 35,000 feet. In-flight turbulence was light until it flew over Mount Fairweather, whereupon turbulence immediately became moderate. Severe clear-air turbulence occurred roughly 30 miles east of Yakutat, Alaska, a region marked by a gray diamond in Figure 2. All three flight attendants were injured, two seriously: those two were at the back of the plane preparing the drinks cart, when they were thrown violently into the ceiling and then the cabin floor by "two massive jolts."

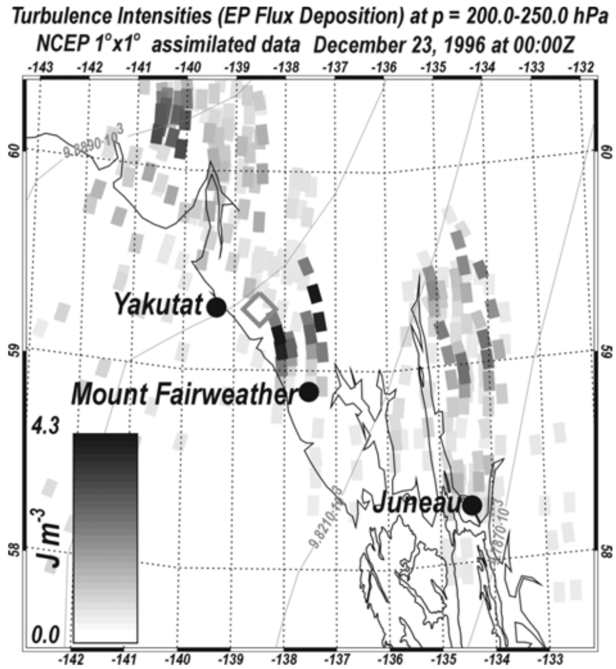

FIG. 2. MWFM 2.0 hindcast of mountain wave-induced turbulence at 200-250 hPa on 23 December, 1996 at 0Z, based on 1°x1° assimilations (see grid) from the National Center for Environmental Prediction. Light gray contours show geopotential heights, which approximate streamlines. Diamond shows estimated location of turbulence incident.

SIGMET advisories indicated no turbulence in this region: however, these advisories did not account for mountain waves. Figure 3 shows results of an MWFM 2.0 hindcast for the region at flight level of the incident, using National Center for Environmental Prediction (NCEP) analysis data for December 23, 1996 at 00:00 UT. We see a zone of mountain wave-induced turbulence predicted between Mount Fairweather and the estimated location of the incident. Given our criterion for "uncomfortable" turbulence of ~1 J m^{-3}, the values of ~2-4.5 J m^{-3} in this region are consistent with the moderate-to-severe turbulence encountered along this flight segment. Interestingly, turbulence was almost entirely absent in the MWFM hindcast at the next level down (250-300 hPa: ~28,000-33,000 feet). Thus, if these forecasts were available at the time, a simple reroute to a slightly lower flight altitude might have avoided this incident.

a. United Airlines Flight 2118: November 19, 1996

This Boeing 737-500 flight from San Francisco to Las Vegas encountered clear air turbulence at flight

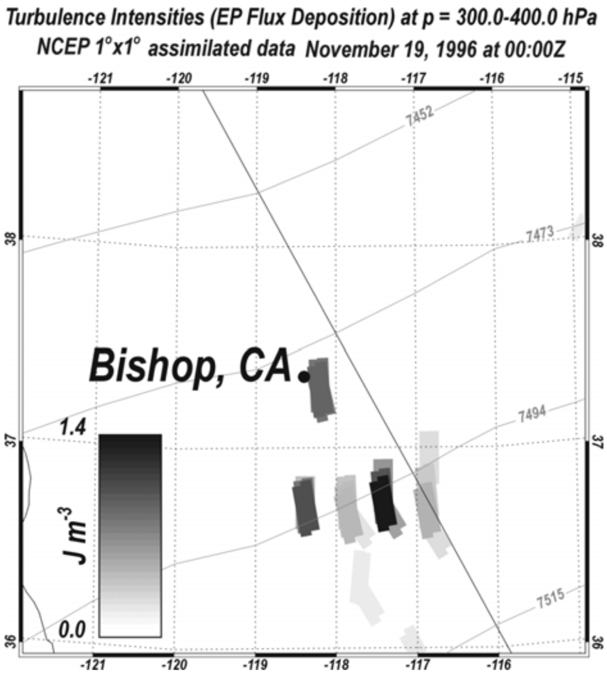

FIG. 3. MWFM 2.0 hindcast of mountain wave-induced turbulence at 300-400 hPa on 19 November, 1996 at 0Z, based on 1°x1° assimilations (see grid) from the National Center for Environmental Prediction (NCEP). Diagonal line shows the California-Nevada border. Contours show geopotential heights.

level 290 (~310 hPa) near Bishop, California. The aircraft dropped suddenly, causing a flight attendant to break her foot. A general “CAT Alert” for the region was in effect, based on previous aircraft encounters with turbulence in the area.

Figure 3 plots an MWFM 2.0 hindcast for November 19, 1996 in the 300-400 hPa height interval, based on NCEP assimilated data for the region. The model hindcasts fairly intense wave-induced turbulence (>1 J m^{-3}) near and just south of Bishop at the airliner’s flight altitude. The largest values here are smaller than those in Figure 2, consistent with what appears here to have been a less violent incident.

The NTSB report (LAX97LA051) indicated that this flight level was chosen because earlier flights reported turbulent rides at higher altitudes. In this specific region, our hindcasts suggested less turbulence just above 29,000 feet but more widespread turbulence of similar magnitude at upper levels (~38,000-42,000 feet).

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